NATIONAL ELECTRICAL STANDARDS

Resistance Standards and Measurement Methods
This project was incorporated into "Quantum Resistance and Capacitance" above.

Quantum Resistance and Capacitance

(Includes former project "Resistance Standards and Measurement Methods")

Project Leader: Randolph E. Elmquist

Staff: 7.0 Professionals, 2.6 Technicians, 1.0 Student

Funding level: $1.8 M

Funding sources: NIST (80%), Other Government Agencies (20%)

Objective: Maintain the U.S. legal ohm and farad; support the Division's resistance and capacitance calibration services; provide industry, academia, and government with calibration services unequaled in scope and accuracy; develop new resistance and capacitance standards and improved measurement techniques; and participate in international comparisons of the ohm and farad and supporting experiments to realize the international definitions of the ohm and farad.

Background: The research work being done on this project is the key to tying the U.S. legal system of electrical units to the international system (SI) of units. Strong support in this research area allows NIST to provide the nation with the world's best basis for electrical measurements and to conduct measurements of the SI ohm and farad that have smaller uncertainties than those of any other nation. NIST’s maintenance of the ohm by the quantum Hall effect -- a resistance standard dependent only on the values of fundamental constants of nature -- and the farad by the calculable capacitor -- a standard dependent only upon an SI length measurement -- provide a solid basis for measurement quality in U.S. industry. The activities of this project underlie the future development of not only the electrical measurement services provided to industry by NIST, but also the development of commercial high-precision instrumentation needed by industry to support advances in electronics. Methods developed by NIST for scaling of impedance measurements at the highest levels of accuracy will provide needed capabilities for extending the measurement range, voltage, and frequency for industry and other government laboratories.

U. S. industry requires accurate resistance and capacitance measurements for both quality and process control purposes. Not only are resistors and capacitors the most commonly used electronic components, they are important control parameters in the manufacture of semiconductor electronics and common tools for the measurement of temperature, pressure, force, light intensity, and other quantities via transducers. NIST's most visible link to these applied measurements is through the instrumentation industry. Accurate, traceable impedance measurements are vital to the development, testing, manufacturing, and maintenance of instrumentation. This is reflected in the volume of calibration work which accounts for about 50% of the Electricity Division's and over 11% of all of NIST's calibration income. The most challenging present needs are for new standards that are environmentally insensitive for supporting *in situ* maintenance of precision meters, ac resistance calibrations to support temperature measurements and calibration of impedance meters, and research to support commercialization of the cryogenic current comparator and quantum Hall effect systems for improved scaling in bench instrumentation.

NIST is uniquely qualified to interact with other national laboratories in the comparison of resistance and capacitance standards and the verification of scaling from the basic standards in support of the worldwide electronic instrumentation industry. Such comparisons ease impediments to international trade.

Current Tasks:

<u>Resistance</u>:

1. Determine the SI ohm

FY 1981	Initiated the development of the capability to determine the SI ohm from the newly discovered quantum Hall effect and the calculable capacitor.
FY 1990	Reported new values of the von Klitzing constant and the SI ohm.
FY 1994	Initiated performance tests of the calculable capacitor chain for an improved determination of the SI ohm.
FY 1996	Determined the SI ohm from the quantized Hall resistance and the calculable capacitor.
FY 1997	Design and construct bridges for an expanded frequency range for the determination of the SI ohm over an expanded frequency range.
FY 1998	Design and evaluate standard resistors for use at multiple frequencies.
FY 1999	Determine the SI ohm using a frequency other than 1592 hertz.

2. Establish and maintain the national standards of resistance

FY 1990	Implemented the January 1, 1990 new representation of the U. S. ohm based on the quantum Hall effect (QHE) and the International Temperature Scale of 1990.
FY 1992	Developed cryogenic current comparator (CCC) measurement system for comparing quantized Hall resistances (QHR) with 100 ohm resistance standards; Verified Hamon scaling process to 0.01 part per million using more accurate CCC ratios.
FY 1993	Completed construction of a third CCC with an additional ratio of 129.06/1 for use in measuring the I=2 step of the QHR; Completed two comparisons of the QHR to the 1 ohm working group.
FY 1996	Characterized 10 megaohm and 1 gigaohm resistance transfer standards and started the first leg of a high resistance international comparison commissioned by the Consultative Committee on Electricity.
FY 1997	Continue ohm maintenance using the QHR measurement system.

3. Provide resistance measurement services for our customers

FY 1994	372 standards calibrated at a cost to industry of $366,000; Completed construction of a guarded coaxial connector panel for switching resistors.

FY 1995	360 standards calibrated at a cost to industry of $338,000; Completed development of an automated 10 kΩ measurement system.
FY 1996	327 standards calibrated at a cost to industry of $329,000; Automated 10 kΩ measurement system installed for customer calibrations.
FY 1997	Continue measurement services; Initiate development of ac resistance bridge.

4. Develop an automated system for the measurement of high resistance standards

FY 1994	Completed design and construction of a temperature/humidity air bath for high resistance measurements.
FY 1995	Completed modifications of an electrometer for use as a programmable detector in an automated high resistance bridge with programmable voltage sources as ratio arms.
FY 1996	Completed development of high resistance automated system and began comparisons with existing systems.
FY 1997	Complete evaluation and documentation of system, construct new Hamon devices to reduce scaling uncertainty, and extend resistance calibration range to 10^{14} ohm.

5. Develop an advanced quantized Hall resistance research and measurement capability

FY 1993	Developed a method of using an electronic voltmeter for realizing the quantized Hall resistance values in the laboratory with sufficiently low uncertainty.
FY 1995	Determined the potential and current distributions in a quantized Hall device for assessing the maximum electric fields for resistance values for both direct current and alternating current.
FY 1996	Acquired and installed a new quantized Hall measurement system for increased magnetic field, variable temperature, and efficient sample exchange capabilities.
FY 1997	Design and build new insert probes with low losses and initiate quantized Hall resistance studies with direct current.
FY 1998	Develop measurement systems for alternating current.
FY 1999	Compare the resistance value of a single quantum Hall device under both dc and ac conditions.

6. Improve the quality and performance of quantized Hall devices

FY 1994	Developed advanced alloy contact techniques for low resistance contacts and new patterning techniques for fabricating heterostructure devices.
FY 1995	Prepared and tested quantized Hall devices made from new low electron density heterostructures using the developed alloy contact techniques.
FY 1996	Determined the equivalent circuit of a quantized Hall device and calculated the intrinsic inductance and capacitance for resistance studies using alternating current.
FY 1997	Publish a summary of quantized Hall device preparation and characterization techniques and test results.
FY 1998	Prepare a quantum Hall device for both dc and ac measurements.

7. Improvement of resistance scaling using cryogenic current comparators (CCC)

FY 1992	Developed method for detecting leakage currents in CCC bridges.
FY 1994	Constructed a prototype high temperature superconductor (HTS) CCC achieving a 1:1 ratio balance to within a part per million.
FY 1995	Consulted with three HTS research companies to push development of state-of-the-art HTS magnetic shields for constructing CCCs; Contracts sent out for the construction of magnetic shields using thallium-based HTS materials.
FY 1996	Constructed a prototype HTS CCC using thick-film thallium-based shields and a YBCO SQUID detector; Measured 1 kilohm/100 ohm ratios with 0.5 parts-per-million uncertainty.
FY 1997	Develop an automated HTS CCC system using improved shields with a combined standard uncertainty of less than 0.1 part per million for measuring resistors from 1 ohm to 10 kilohm.
FY 1998	Complete evaluation of HTS CCC system and provide adequate documentation for commercialization.

<u>Capacitance</u>:

1. Realize the SI farad

FY 1960	Initiated construction of a calculable capacitor in order to connect the national units of impedance with the SI units.
FY 1974	Reported the determination of the SI farad from the calculable capacitor.
FY 1980	Initiated construction of a new, improved version of the calculable capacitor.
FY 1988	Determined the SI farad from the calculable capacitor.
FY 1993	Improved the conical nose piece that provides the end compensation for the calculable capacitor as part of continued improvements.
FY 1994	Evaluated the uncertainties in the calculable capacitor chain.
FY 1996	Reported a new value for the calculable capacitor determination of the SI farad.
FY 1997	Design and construct bridges for use with an extended frequency range for the calculable capacitor chain.
FY 1998	Determine the SI farad at one alternate frequency.
FY 1999	Design and evaluate capacitors for alternate frequencies for the calculable capacitor chain.

2. Provide the national unit of capacitance

FY 1994	Designed and assembled a capacitance bridge with the potential for a wider frequency range bracketing the value presently used (1592 hertz).
FY 1996	Provided the value of the national farad capacitor bank for calibration services with an uncertainty of 0.002 parts per million; Initiated an international comparison of capacitance for the Consultative Committee on Electricity;
FY 1997	Determine the effect of the mounting method of the capacitance elements on the temperature dependence of the reference capacitors.
FY 1998	Complete the international comparison of capacitance and provide results and interpretation to the Consultative Committee on Electricity.

Quantum Voltage and Current

Project Leader: Edwin R. Williams

Staff: 6.0 Professionals, 3.0 Guest Scientists, 1.0 Postdoc

Funding level: $1.3 M

Funding sources: NIST (89%), Other Government Agencies (4%), Other (7%).

Objective: Maintain the U.S. legal volt; support the Division's voltage calibration services; and develop new voltage and scaling standards, measurement techniques, and means of disseminating the volt. Measure the U.S. unit of current as established from national resistance and voltage standards in terms of the internationally defined ampere; monitor the kilogram in terms of electrical units via the watt experiment; and determine the gyromagnetic ratio of the proton in terms of the U.S. electrical units. Apply the physics of these measurements and other new phenomena, such as single electron tunneling, to the development of improved measurements and standards, especially for current standards.

Background: The services provided by this project generate the basis for accuracy and compatibility for all voltage and current measurements throughout U.S. industry, technology, and science. The standards being produced by this project tie the U.S. legal system of electrical units to the international system (SI) of units permitting competitive products by U.S. industry in world markets. The research being done is the source of superior drift-free, high precision national standards for the volt and the ampere (and assists in the ohm and farad). The work also involves evaluating new measurement techniques and standards for automated and highly accurate dissemination of these units. Another very significant effect of this research focuses on the creation of an electronic replacement for the kilogram, the last remaining SI artifact standard, and exploring the application of the new single electron tunneling phenomena to the determination of the electronic charge or the fine structure constant or for application as a capacitance standard.

Current Tasks:

<u>Voltage</u>:

1. Provide the national unit of voltage

FY 1993	Developed methods for calibration of the high accuracy digital voltmeters using the 10 volt Josephson array.
FY 1994	Monitored the values of solid state voltage references for stability and noise and characterized behavior during measurement intervals.
FY 1995	Tested the applicability of the new 10 volt Josephson arrays for research purposes in monitoring the value of solid state voltage references.

FY 1996	Replaced the computers that operate the Josephson 1-volt system and developed improved software for the operations and data analysis.
FY 1997	Provide the values of three transfer, solid state voltage references in terms of the Josephson volt to the NIST voltage calibration laboratory with an uncertainty of 0.05 microvolt/volt.
FY 1998	Characterize Zener solid state voltage references for both short- and long-term noise characteristics as a function of measurement intervals.
FY 1999	Perform a direct array-to-array comparison of the U.S. national voltage standard system with that of the National Research Council of Canada.

2. Improve the reliability of the voltage calibration systems

FY 1993	Rewired the voltage calibration benches for improved thermal noise characteristics and voltage stability.
FY 1994	Rewired the automatic switches that control the voltage calibration benches and the switching of customers voltage references for a three-fold increase in capacity.
FY 1995	Replaced the computers that operate the calibration benches for more efficient operation and greater capacity.
FY 1996	Provided voltage calibration services for customers' voltage references with an uncertainty of 0.2 parts per million.
FY 1997	Reevaluate the operational software for the voltage calibration system and modify with the necessary improvements for increased efficiency and capacity.
FY 1998	Purchase and install a 10-volt Josephson array system as an integral part of the voltage calibration system.

Current:

1. Determine the value of the NIST watt

FY 1992	Incorporated a superconducting magnet into the ampere balance for improved signal-to-noise performance and increased precision.
FY 1995	Redesigned the process for the alignment of the magnetic field, the coil motion, and the earth's gravitational force for reduced uncertainties.
FY 1996	Decreased the short term uncertainty to 0.1 parts per million; Installed the new refractometer for the determination of the index of refraction and the new gravimeter for a more precise determination of the gravitational constant.
FY 1997	Determine a value for the NIST watt with a total uncertainty of 0.1 parts per million; Begin conversion to improved system for monitoring the kilogram.
FY 1998	Complete system automation, incorporating refractometer, gravimeter, and Josephson array into real time measurements.

2. Initiate redesign of the NIST watt experiment for the next generation of improvements

FY 1995	Initiated the redesign of the NIST watt experiment with the objective of monitoring the kilogram.
FY 1996	Redesigned the NIST watt experiment to include vacuum or gas environment.

FY 1997	Initiate construction of the vacuum enclosure for the watt balance and reconstruction of the watt balance room.
FY 1998	Monitor a kilogram mass with a continued precision of 0.1 parts per million.
FY 1999	Monitor a kilogram mass with a precision of <0.1 parts per million.

3. Demonstrate a single electron tunneling electrometer

FY 1993	Initiated studies for the application of single electron tunneling devices to metrological experiments such as capacitance calibrations.
FY 1994	Developed the capability to fabricate single electron tunneling devices.
FY 1995	Demonstrated the application of a single electron tunneling electrometer as the detector in a cryogenic capacitance bridge to determine a capacitance ratio to a few parts per million.
FY 1996	Performed measurements demonstrating the extraordinarily low leakage of the single electron tunneling electrometer and cryogenic capacitor system; Began charge noise measurements.
FY 1997	Combine the NIST Boulder electron pump and the capacitance bridge and cryogenic capacitors to demonstrate a capacitance calibration using single electron tunneling technology; Continue charge noise and initiate charge offset studies.
FY 1998	Continue and refine capacitance calibration experiment with NIST Boulder.
FY 1999	Transfer/duplicate capacitor calibration experiment to NIST Gaithersburg for direct comparison to the calculable capacitor.

4. Provide magnetic field calibration services to the Navy Primary Standards Laboratory

FY 1993	Designed a low magnetic field calibration system for use at the Navy Primary Standards Laboratory.
FY 1994	Fabricated a low magnetic field calibration system.
FY 1995	Delivered the magnetic field calibration system to the Navy Primary Standards Laboratory, San Diego, California and initiated training of Navy personnel.
FY 1997	Complete training of Navy personnel and provide consultation on the implementation of the low magnetic field calibration system into the U.S. metrological system.